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APOLLO SATURN 511 EFFLUENT MEASUREMENTS FROM THE APOLLO 16 LAUNCH OPERATIONS - AN EXPERIMENT

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16. Abstract

An experiment was performed in conjunction with the Apollo 16 launch to define operational and instrumentational problems associated with launch-vehicle exhaust effluent monitoring. Ground and airborne sampling were performed for CO, CO_2, hydrocarbons, and particulates. Sampling systems included filter pads and photometers for particulates and whole-air grab samples for gases. Launch debris was identified in the particulate samples at ground level (taken immediately after launch) and in the airborne measurements (taken 40 to 50 minutes after launch approximately 40 km downwind of the pad). Operational problems were identified and included the need for higher instrumentation mobility and the need for real-time sampling instrumentation as opposed to collection-type samples such as the whole-air grab sample.

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SUMMARY

On April 16, 1972, Apollo 16 was launched from Kennedy Space Center, launch complex 39 A, at 1754 UT (12:54 EST). As part of a program to study the diffusion and dispersion of launch-vehicle exhaust effluents, an experiment was performed during the launch to define the operational problems and to evaluate the instrumentation associated with launch-vehicle effluent monitoring. Secondary objectives were to obtain some data on the initial composition and concentration of the exhaust cloud as it was formed and mixed with the atmospheric air, but before it rose from the ground, and to obtain effluent measurements in the stabilized cloud as it drifted downwind and dispersed. The experiment included in situ ground-level and airborne effluent measurements for CO, CO_2, hydrocarbons, and particulates. Airborne sampling techniques employed filter pads for particulates and grab samples for the gaseous species. Ground sampling included filters and photometers for particulates and grab samples for the gases. Ground sampling was performed approximately 400 meters from the launch point; whereas, airborne sampling occurred from 2 to 40 km from the launch point. Ground sampling indicated that the exhaust cloud has substantial quantities of launch debris. This debris was present in airborne particulate samples taken approximately 40 km downwind of the launch at 40 to 50 minutes after launch. Gas sampling at three ground level sites showed no gas species attributed to the launch. Airborne sampling at 40 km downwind and at an altitude of 2200 meters showed CO from the launch in concentrations of 7 to 9 ppm. Operational problems were defined and included (1) the need to have highly mobile sets of instrumentation capable of being sited as late in the launch countdown as T-4 hours, (2) the need to use real-time instrumentation rather than collection type samples like whole-air grab samples, and (3) the need to document locations of airborne sampling accurately.

INTRODUCTION

This report summarizes the effluent measurements during the joint NASA Marshall Space Flight Center (MSFC) and Langley Research Center (LaRC) booster

effluent dispersion monitoring experiment for the Apollo Saturn 511 vehicle. The Apollo 16 mission was launched from the NASA Kennedy Space Center (KSC) launch complex (LC) 39 A on April 16, 1972, at 1754 UT (12:54 EST).

This experiment included the in situ ground-level and airborne measurements of the dispersion of the Saturn S-1C booster engine exhaust effluent. Preflight wind-direction predictions 2 months prior to launch were used to position the effluent measurement equipment. Airborne measurements were made with the aircraft configured for routine aerial air quality surveys. The postflight calculations of the diffusion of the Apollo 16 exhaust cloud using the MSFC multilayer diffusion model are not reported herein.

The authors acknowledge the cooperation and support of Kennedy Space Center and the U. S. Air Force during the experimental measurement program.

OBJECTIVES

The objectives of the experiment were to define the operational problems and to evaluate instrumentation requirements associated with launch-vehicle effluent monitoring. Secondary objectives were to obtain some data on the initial composition and concentration of the effluent cloud as it was formed and mixed with the atmosphere but before it rose from the ground, and to obtain measurements (airborne) in the stabilized ground cloud as it drifted downwind and dispersed.

PROGRAM DESCRIPTION

Launch Vehicle

The Saturn V is a three-stage Apollo Saturn launch vehicle developed by NASA to support the Apollo lunar landing missions. With the Apollo spacecraft, it is about 110 meters (363 ft) tall and weighs nearly 2.9×10^6 kilograms (3200 tons). The first stage, Saturn S-1C, is 42 meters (138 ft) tall and 10 meters (33 ft) in diameter and uses five Rocketdyne F-1 engines, each of which produces a thrust of 6.7 meganewtons (1.5×10^6 pounds force) and uses a mixture of liquid oxygen (LOX) and RP-1 as propellant. The five engines consume 1.84×10^6 kilograms (4.06×10^6 pounds mass) of propellant in about 160 seconds and lift the vehicle to an altitude of approximately 70 kilometers (43.5 miles) as shown in table I.

The exhaust effluent emitted by this stage consists primarily of water vapor (H_2O), carbon monoxide (CO), and carbon dioxide (CO_2). Of these gases, only CO is toxic. A summary of the exhaust products is shown in table II.

Measurement Systems

The measurement systems for the Apollo 16 launch effluent experiment were located at three ground instrumentation sites and on four fixed-wing aircraft. Ground site locations were selected approximately 2 months prior to launch based on predicted surface winds out of the southeast. Figure 1 shows the ground site locations and the instrumentation used. The actual surface winds at launch (from 240°) were obtained from MSFC. Ground site equipment was selected to determine the effluent composition and concentration of the initial booster engine exhaust cloud. Airborne sampling was on a real-time basis either as directed by ground voice communication or by airborne visual cloud sightings. Aircraft sampling was directed at obtaining effluent dispersion measurements. Two aircraft were designated to sample the stabilized ground cloud below the 3-km inversion level and two additional aircraft were to sample the rocket exhaust plume in the altitude range of 3 to 18 km.

Each sampling platform, ground and airborne, was equipped to obtain gas samples. Camera pad 5 and the aircraft were also equipped for sampling particulates. Table III describes the equipment and its intended function. Incorporated into the sampling schedule was appropriate prelaunch gas and particulate samples to establish the effluent background at each site prior to the Apollo 16 launch. Gas and particulate grab samples were returned to the laboratory for analysis. Gas samples were analyzed for CO, CO_2, and hydrocarbons by infrared, gas chromatography, and mass spectrometry techniques. Mass spectrometry was used only on those samples where infrared and/or gas chromatography showed evidence of hydrocarbon presence. The lower limit of detection was 1 ppm with an analysis accuracy of ± 1 ppm for CO and 10 ppm $\pm$ 10 ppm for CO_2. Analysis of the particulates was directed at identifying the chemical elements present by using techniques such as atomic absorption, electron microprobe, and beta probe analyses. The laboratories participating in the gas and particulate analysis were: NASA Langley Research Center; NASA Kennedy Space Center; McClellan central laboratory of the U.S. Air Force; Raleigh laboratory of the Environmental Protection Agency; and the Washington, D.C. laboratory of the National Bureau of Standards.

RESULTS AND DISCUSSION

Since some data are only of interest for future program planning and add no insight either in confirming model predictions or understanding the effluent dispersion problem, only the results pertinent to the program objectives will be discussed.

Atmospheric Conditions

The atmospheric conditions in the vicinity of KSC launch complex 39 A (1804 UT) on April 16, 1972, as reported by MSFC, were influenced primarily by dry stable air associated with an anticyclonic system centered off the east coast of Florida. Locally, there were only a few scattered cumulus clouds with bases at about 2 km. A sea breeze had penetrated inland from the southeast across much of Cape Kennedy, but had not reached as far as launch complex 39 A. The wind was from the southwest at almost all altitudes from the surface to an altitude of 20 km as shown in figure 2. These persistent southwest winds were responsible for delaying and reducing the effect of the sea breeze. Wind speeds ranged from 6.3 m/sec at an altitude of 3 meters to a maximum of 26.1 m/sec at an altitude of 11.9 km. At the time of the Apollo 16 launch, a subsidence inversion existed over KSC, with a base at about 2000 meters. This inversion was the controlling influence on the rise and stabilization altitudes of the exhaust ground cloud.

Ground-level time-lapse photographs (taken approximately 5.5 km west of the pad) of the Apollo 16 ground cloud were used to define the stabilization altitudes. At T + 150 seconds, the cloud was observed to be mixed with the atmosphere and at an altitude of approximately 2 km. At this time the cloud was observed to be 800 meters high (Z-axis) and 2000 meters in both the X and Y axes. It was also determined from these photographs and the vehicle trajectory that the first 43 seconds of engine operation (5.46×10^5 kg of propellant) emitted effluents into the ground cloud.

Effluent Measurements

Ground level. - A total of 14 gas grab samples were taken at camera pads 2, 5, and 6 located on launch complex 39 A. Grab samples were collected by use of evacuated stainless-steel cylinders which were remotely vented to the atmosphere by a solenoid valve to take the gas sample. Samples were collected at times ranging from T - 10 seconds (background) to T + 3 minutes. Background samples showed the normal air constituents in the correct ratios. No evidence of launch effluent was found in the gas samples taken after T zero. Ground photographic coverage indicated that none of the three camera pads used for sampling fell within the initial cloud path. The combination of the southwesterly winds, cloud dynamics at exit from the flame trench (oriented north to south), and cloud buoyancy is believed to have caused the cloud to fail to engulf the camera pads. The only ground-level measurements taken which help to identify the initial cloud concentration were the particulate samples taken at camera pad 5, the only ground site at which particulate samples were taken. Figure 3 shows the particulate activity measured at 1-minute intervals at camera pad 5 during the launch. Zero time on the figure is vehicle lift-off. At approximately T + 1 minute, a sizable increase in the particle count for all ranges of particle sizes was measured. The normal ambient particle count is represented by the data from 4 to 20 minutes after launch.

The data of figure 3 were obtained with a Climet light-scattering particle counter using a sampling rate of 7.1 liters per minute (0.25 ft^3/min). In addition to the Climet data, particle samples were collected with high-volume, Andersen, and Millipore systems. Laboratory analysis of these particles showed the elemental constituents to be sodium, aluminum, chlorine, calcium, titanium, iron, and tungsten. Prelaunch ambient particle samples showed calcium, silicon, chlorine, and sodium. The increase in particle count observed at launch indicates that a particulate cloud passed through camera pad 5; whereas the elemental analysis of the collected particles showed these particulates to be primarily ground dust and launch debris. The absence of detection of gas species at camera pad 5 indicates that possibly the observed particulate cloud was generated from overpressures from the rocket and that the carrier medium for the particulates was ambient air rather than exhaust species. It can also be speculated that at camera pad 5, even if the cloud had gone overhead, the gaseous species may have enough buoyancy that they would not be detected at ground level by a grab sampling device.

Airborne samples. - Gas and particulate samples from the high-altitude (3 to 18 km) aircraft showed no evidence of launch effluent. Low-altitude (0 to 3 km) samples showed evidence of launch effluent. Table IV summarizes these low-altitude particulate results. Samples were also analyzed for aluminum, chromium, potassium, and lead. These analyses showed only background levels for all the samples. Each sample was taken in a visible cloud. Particulate samples were collected on IPC 1478 filter papers impregnated with kronisol that were inserted into the air sampling system of the aircraft. Sampling times and exposure times are given in table IV. The data of table IV indicate that these particulate samples were taken in the stabilized ground cloud since the iron content of each sample is high when compared with the prelaunch background; this result was also observed for the ground samples at camera pad 5. In addition, the sampling altitudes and time after launch are in agreement with the photographic observations that at 2.5 minutes, the cloud was stabilized at 2200 meters.

None of the particulate samples of table IV could be used to confirm quantitatively the MSFC dispersion model. The particulates collected were high in structural or launch debris constituents and the model inputs to account for debris is unknown. In addition, only elemental identification of the carbonaceous particles was possible.

Corresponding to particulate sample 5 are two companion gas samples taken downstream of the filter (sample 5) in the aircraft sampling system. The gas samples were obtained by simultaneously pumping the gas in the sampling system into two 30-cm-diameter (12-in.) stainless-steel spheres. The spheres were pressurized from atmospheric pressure to approximately 10 atmospheres with the gas sample. Independent laboratory analyses of the gas samples (one sphere to each laboratory) for CO, CO_2, and total hydrocarbon are shown in table V (background has been subtracted). Hydro-

carbon analysis was performed only by one laboratory and revealed 7.9 ppm. The CO_2 analyses did not agree. A duplicate analysis was only possible at the Langley laboratory and this analysis confirmed the 10-ppm concentration. The CO concentration as measured by both laboratories was approximately 8 ppm. The manner in which these gas samples were collected negates the possibility of a direct comparison of these measured results with MSFC model predictions. The samples were taken over a 15-minute period (see table IV) with the aircraft flying in and out of a visible cloud and changing altitudes from 1.8 to 3 km. There is no way to account accurately for dilution while the aircraft was outside the visible cloud nor is it possible to know at which altitude most of the launch sample was obtained. In addition, the aircraft's reported location (aircraft was not radar tracked) and the predicted cloud movement do not completely coincide. The aircraft is estimated to have taken the sample 38.4 km east of Cape Kennedy; MSFC predicted that the cloud would diffuse along a radial of 69.5° from the pad. Although these directions do put the aircraft and predicted cloud in the same general area, the aircraft data are inconclusive insofar as accurately defining the sampling location.

However, for comparison with the model, the following assumptions concerning the aircraft data (sample 5) can be reasonably applied:

(1) The sampling altitude is 2200 meters, the center line of the stabilized ground cloud.

(2) The sample dilution factor is approximately 30 percent. (This estimation is based on the visible cloud.)

(3) The aircraft location during sampling was 40 km downwind in the direction predicted by the model.

Based on these assumptions and using MSFC model calculations, the average CO concentration in the cloud at 40 km downwind and at an altitude of 2200 meters would be 10 to 13 ppm for CO and 4 to 5 ppm for CO_2.

CONCLUDING REMARKS AND RECOMMENDATIONS

An experiment was performed in conjunction with the Apollo 16 launch to define operational and instrumentational problems associated with launch-vehicle exhaust effluent monitoring. Ground and airborne sampling was performed for CO, CO_2, hydrocarbons, and particulates. The results of the effluent measurement experiment may be summarized as follows:

1. The initial exhaust cloud composition was not determined. The gas species and concentration of this initial cloud is still an unknown and the effluent source inputs, presently based on estimated reactions with the atmosphere, to the dispersion model are unverified.

2. The particulate composition of the ground exhaust cloud was found to consist of launch debris and carbonaceous particles. Launch debris was found in the initial cloud (T + 1 minute) and was still plentiful in the cloud samplings at cloud stabilization altitude (2200 meters) as long as T + 1 hour and as far downwind of the launch pad as 38 km.

3. The ground exhaust cloud was observed to stabilize (at center line of cloud) at about 2200 meters altitude at about T + 2.5 minutes. Aircraft sampling confirmed this stabilization altitude and showed the cloud to be visible and stabilized at approximately 2200 meters at T + 1 hour.

4. Airborne sampling at approximately 38 km east of the launch showed CO concentrations of 8 ppm. Because of uncertainties in sampling procedures, direct comparison of this measurement with model predictions is not recommended.

The following recommendations are presented for future booster effluent prediction and measurement programs:

1. Approximately 2 to 3 months prior to each launch monitoring effort, the Marshall Space Flight Center model diffusion calculations should be run for the launch vehicle of interest and for several anticipated sets of meteorological conditions. These predictions will provide a baseline for the measurement program so that site locations, equipment selection, and sampling procedures may be established.

2. Selection of instrumentation sites for confirmation of ground level effluent predictions should be made as near launch time as possible. A goal might be final site selections as late as T - 4 hours based on model predictions with the best forecast of launch time weather. Such a scheme of operation would require a high degree of instrument mobility as well as frequent dispersion model calculations starting at about T - 3 days and continuing through launch.

3. Measurements should continue to determine the initial ground cloud composition. Airborne measurements should be made as soon as the exhaust cloud reaches stabilization altitude. These measurements are needed to evaluate model source inputs, which are based on estimated post nozzle exit plane chemistry.

4. Ground-level measurements of effluent dispersion should be made at distances and directions from the launch pad where the model predicts maximum ground-level concentrations. These sites will usually be 2 to 20 km from the launch pad.

5. Airborne measurements in the stabilized ground cloud as a function of downwind distance should continue. Although from the local ecology viewpoint, deposition of effluent on the ground is of most interest, cloud concentrations tend to be one or two orders of magnitude higher than ground concentrations and within the detection limits of existing equipment. In addition, the model does predict in-cloud concentrations and some comparisons with the model are possible.

6. Measurement systems should be directed toward in situ and remote real-time instrumentation. Collection type grab samples are difficult to interpret because of the chemistry of the effluent species and reactions with the sample cylinder. In addition, operational problems exist in predetermining the time sequence for sample cylinder opening and closure.

7. Airborne photographic documentation of the ground cloud movement is needed. Not only will this documentation provide additional accuracy in determining the initial volume of the stabilized ground cloud (a model input), but will also verify the cloud passage over instrumentation sites.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., October 30, 1973.

TABLE I.- EXHAUST MATERIALS EMITTED AS A FUNCTION OF ALTITUDE FROM THE S-1C STAGE

[Table supplied by Marshall Space Flight Center]

Altitude range, km	Range time at top of layer, sec	Exhaust material emitted, kg
0 to 2	36	5.460×10^5
2 to 4	49	1.690×10^5
4 to 6	58	1.170×10^5
6 to 8	66	1.040×10^5
8 to 10	72	7.800×10^4
10 to 12	78	7.800×10^4
12 to 14	83	6.500×10^4
14 to 16	88	6.400×10^4
16 to 18	92	5.200×10^4
18 to 20	96	5.200×10^4
20 to 22	100	5.200×10^4
22 to 24	104	5.200×10^4
24 to 26	107	3.900×10^4
26 to 28	110	3.900×10^4
28 to 30	113	3.900×10^4
30 to 40	128	1.950×10^5
[a]40 to 50	140	1.456×10^5
50 to 60	151	1.444×10^5
60 to 70	160	9.360×10^4

[a]Layer in which IBECO occurs; only four engines burn after T + 135.96 seconds.

TABLE II.- F-1 EXHAUST COMPOSITION

[Table supplied by Marshall Space Flight Center]

Component	Weight at exit, percent
H_2	1.13
OH	.22
H_2O	26.6
O	.005
O_2	.011
CO	42.2
CO_2	27.8
CHO	.002
H	.022
HC	1.60
Particulates	.0575
NO_X	0

TABLE III.- AIR QUALITY SAMPLING INSTRUMENTATION

Instrument site location	Equipment	Function	Analysis laboratory
All ground sites; all aircraft	Stainless-steel gas cylinder	Time-sequence collection of gas samples for laboratory identification of composition and concentration.	NASA Langley NASA Kennedy USAF McClellan EPA Raleigh NBS Washington
All aircraft	Filter paper particle sampler	Collection particulates for return to constituent and gravimetric analysis.	NASA Langley USAF McClellan
Ground site	Mass spectrometer	Real-time identification of gas species.	NASA Langley
	Light-scattering photometers	Real-time particulate size and number distribution.	NASA Langley
	High-volume particle sampler	Collection of particulates for return to laboratory for constituent and gravimetric analysis.	NASA Langley
	Andersen particle sampler	Time-sequence collection of particulates for return to laboratory for constituent analysis, aerodynamic sizing, size number distribution, and gravimetric analysis.	NASA Langley
	Millipore particle sampler	Time-sequence collection of particulates for return to the laboratory for constituent and gravimetric analysis.	NASA Langley
	Lundgren particle sampler	Collection of particulates according to size for return to the laboratory for analysis.	NASA Langley

TABLE IV.- AIRBORNE PARTICLE RESULTS

Sample	Time of sample,[a] min	Altitude, km	Location,[b] km	Elemental composition,[c] mg/cm^2	
				Iron (Fe)	Sodium (Na)
Prelaunch[d]	Prelaunch	0.9	9.6; W	6.09×10^{-4}	1.12×10^{-3}
1	T + 11	2.0	2.2; ENE	8.42×10^{-4}	1.12×10^{-3}
2	T + 15	2.0	(e)	2.51×10^{-3}	1.43×10^{-3}
3	T + 16	2.2	(e)	2.41×10^{-3}	1.31×10^{-3}
4	T + 21	2.2	(e)	2.51×10^{-3}	1.33×10^{-3}
Prelaunch[f]	Prelaunch	4.6	60; NNW	3.53×10^{-4}	6.97×10^{-4}
5	T + 46 → T + 61	1.8 → 3.0	38; E	9.08×10^{-3}	1.69×10^{-3}

[a]Time 0 is launch.

[b]Location with respect to launch complex 39 A: distance; direction.

[c]Weight of material per square centimeter of filter pad as analyzed by atomic absorption techniques.

[d]Background corresponding to samples 1 to 4.

[e]Exact location not known; estimated to be ENE, 2.2 to 6 km from launch point.

[f]Background corresponding to sample 5.

TABLE V.- ANALYSIS OF AIRBORNE INCLOUD GAS SAMPLE 5

Background analysis by both laboratories of prelaunch samples taken at approximately T - 10 minutes showed

Total hydrocarbon (LaRC only)	<0.1 ppm
CO	<2.2 ppm
CO_2	330 ppm

Laboratory	Carbon monoxide CO, ppm	Carbon dioxide CO_2, ppm	Total hydrocarbon (methane units), ppm
NASA Langley	7.2	10	7.9
USAF McClellan	8.7	0	Not analyzed

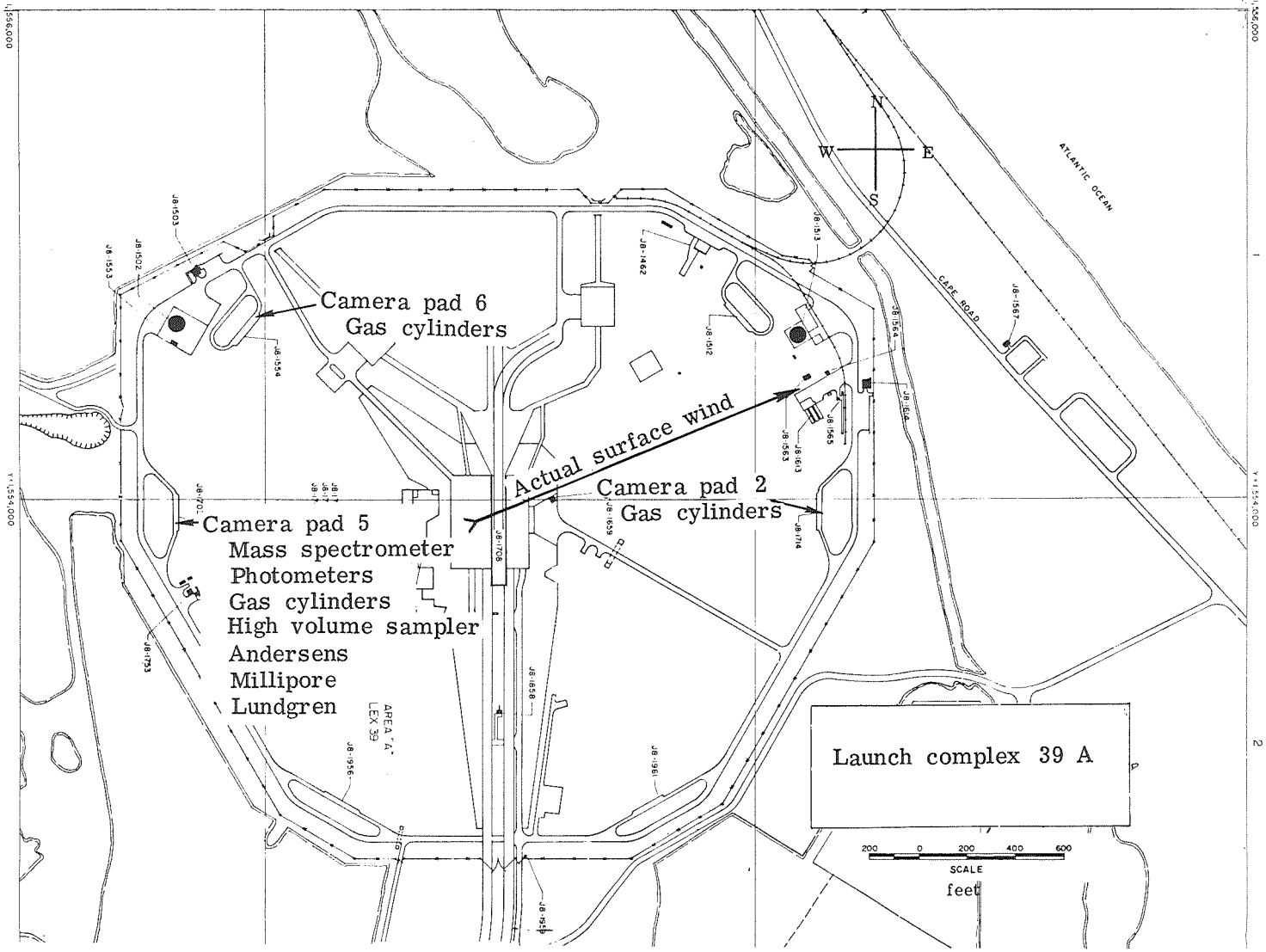

Figure 1.- Ground-level instrumentation and site location.

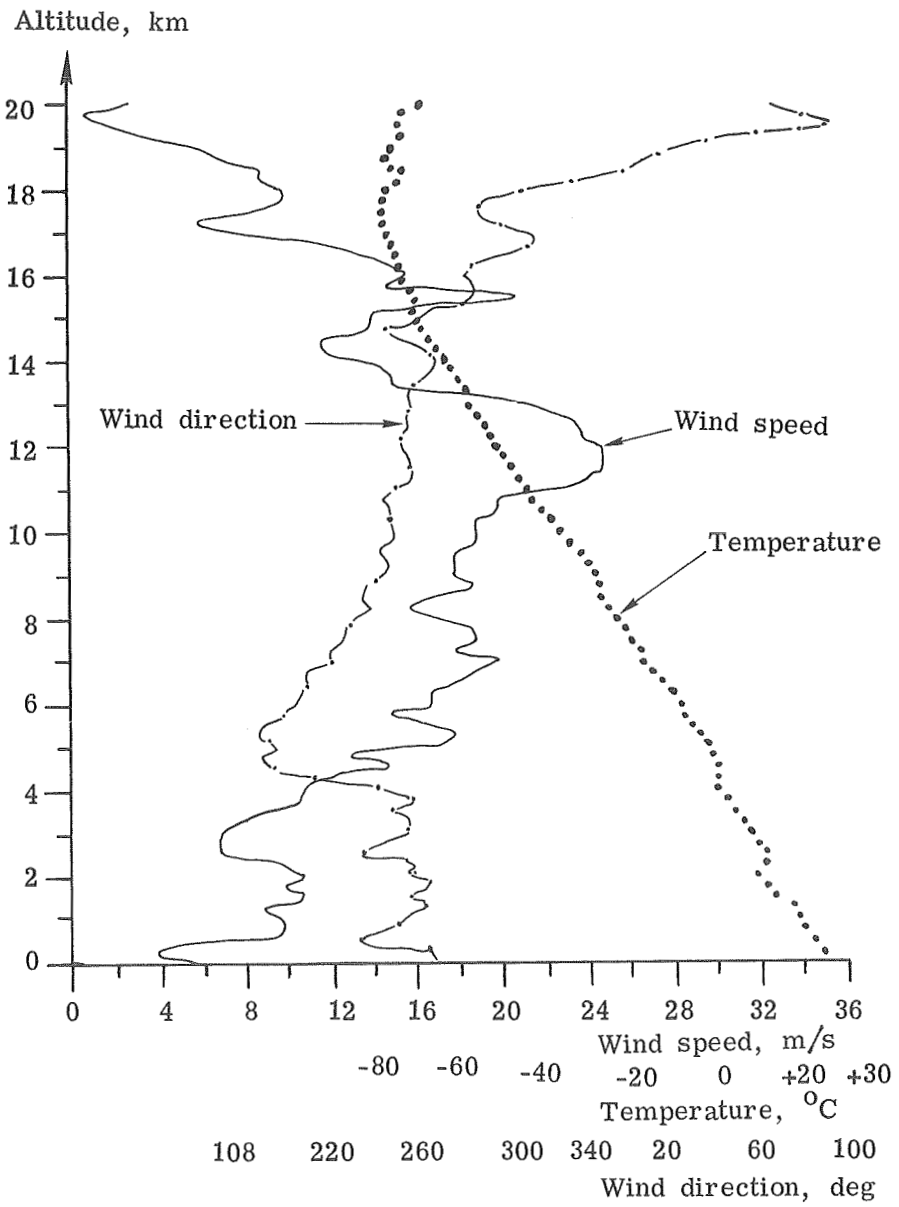

Figure 2.- Wind and temperature profiles for Apollo 16 launch (T + 10 minutes, 1804 UT, April 16, 1972).

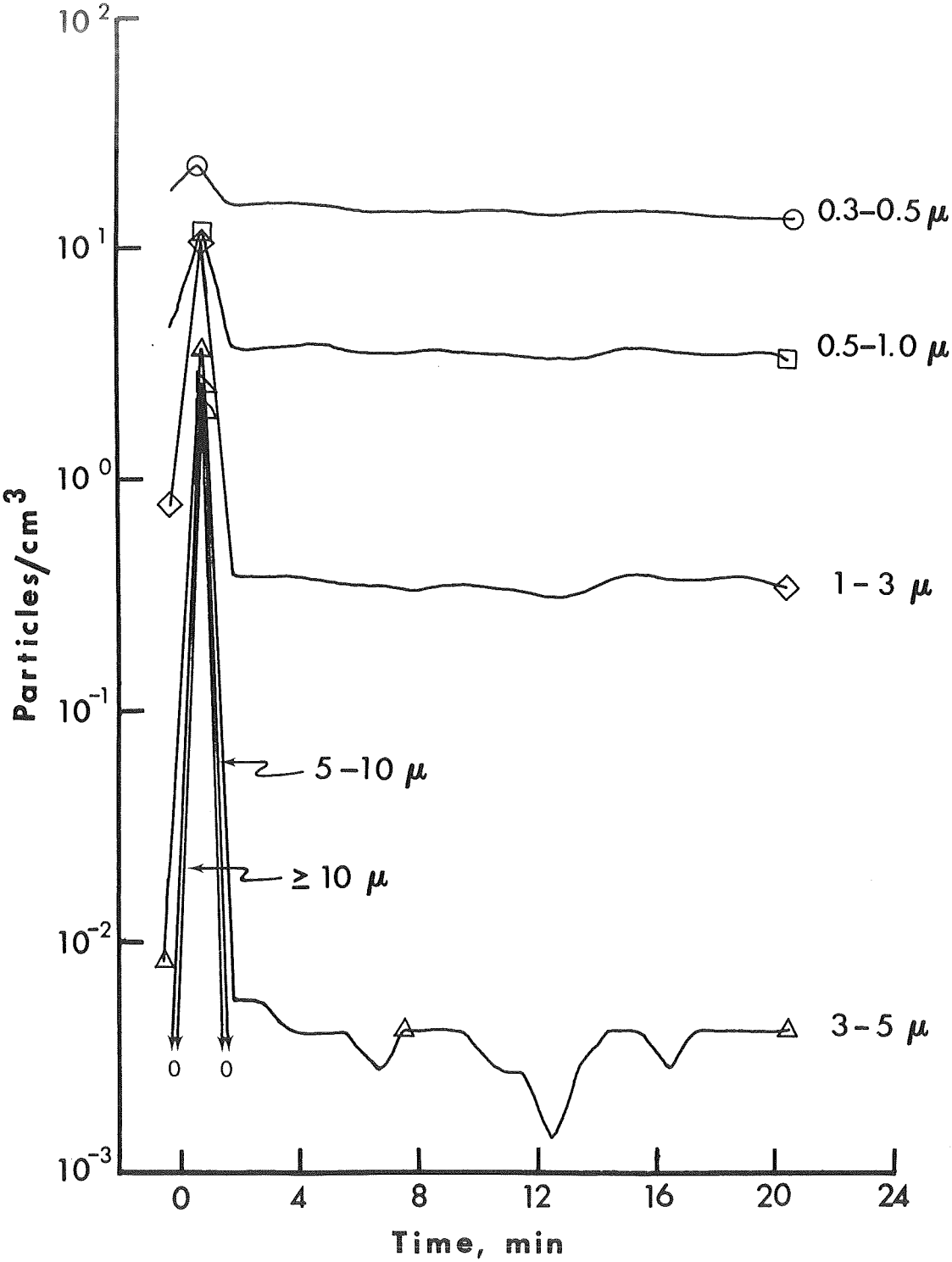

Figure 3.- Particulate activity at camera pad 5 (launch complex 39 A) during Apollo 16 launch.

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